# Federal Transit Administration
# 27th Annual Engineer's Week

Transit Tunnel Design and Construction Considerations

June 2, 2011

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Director of Tunneling

Hatch Mott MacDonald

## Topics

- Types of Tunnels
- Design Considerations
- Subsurface Conditions
- Construction Methods
- Risk Management
- Contract Delivery Methods

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## Tunnel Types

- As defined by function
  - Running tunnel – single or dual track
  - Station – binocular, cavern, or stacked
  - Cross over
  - Cross passage
- Shape
  - Based on function and ground conditions

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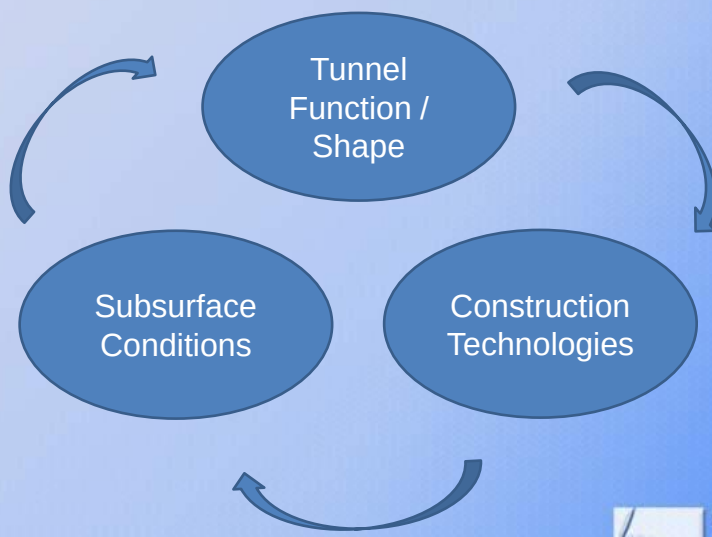
## Tunnel Function and Shape

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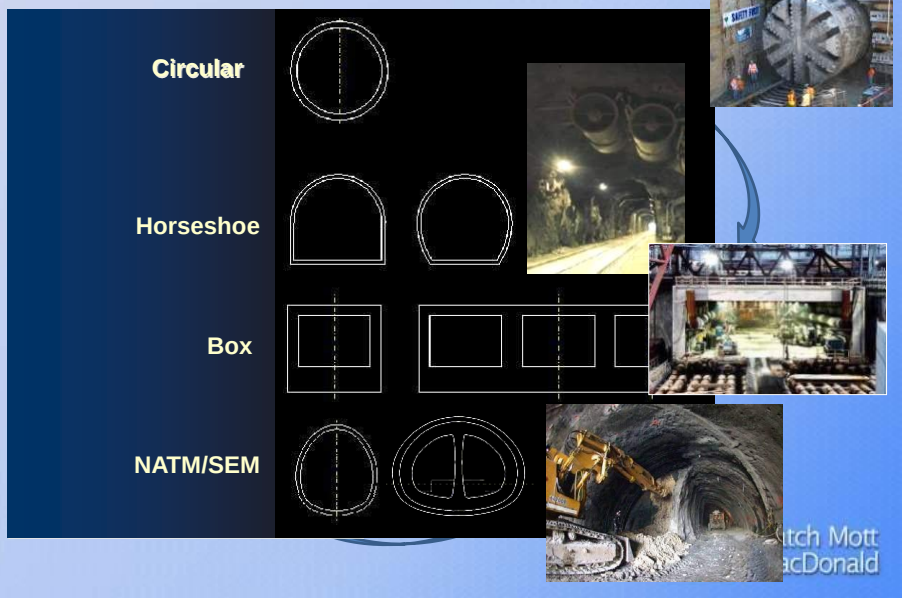
## Tunnel Function and Shape




## Design Considerations

- Horizontal curves
  - Curvature vs design speed
  - Dynamic envelope
- Vertical curves / grades
  - Heavy rail – 2 to 2.5%
  - Light rail – 6%
- Alignment depth
  - Hydrostatic pressure
  - Buoyancy (uplift)

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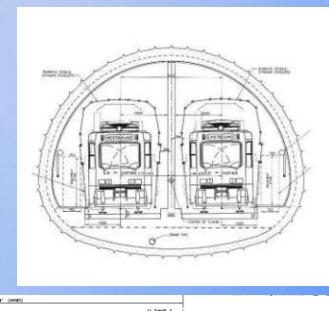
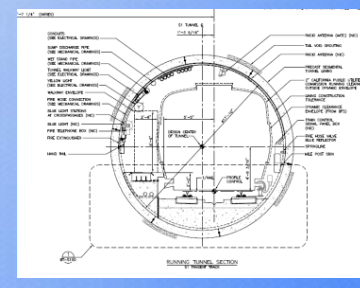
## Cross Section Clearance

- Rail bed, track ties, top of rail
- Dynamic envelope (function of speed and curve radius)
- Emergency walkway
- Catenary (LRT)
- Circular (single track)
- Compound (dual track)





## Complex Transitions

- East Side Access
- Tunnel Wye's to accommodate bifurcations



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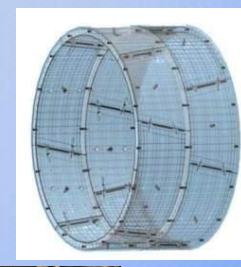
## Lining Design

- Lining principles
  - Ground/structure interaction
  - The ground supports the lining and vice versa
- Long-term loads
  - Ground
  - Groundwater
- Short term loads
  - Handling (casting, erection)
  - Machine thrust



## Tunnel Systems

- Ventilation
- Drainage
- Traction Power
- Fire suppression
- Emergency egress
- Signaling

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## Ventilation Design

- Longitudinal (push/pull)
- Transverse
- Semi-transverse
- Uni-directional traffic
- Bi-directional traffic

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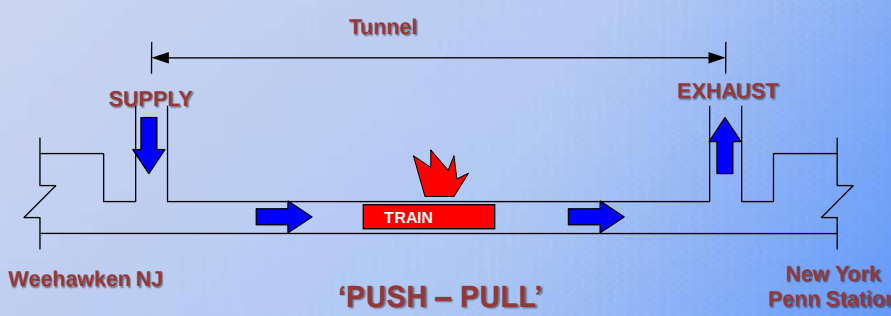
## Rail Tunnel Ventilation

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## Subsurface Conditions

- Hard Rock
  - Sedimentary (sandstones)
  - Igneous (granites, basalts)
  - Metamorphic (schists, gneiss)
- Soft Rock
  - shales, claystones, siltstones
- Discontinuities
  - Joints, shears, faults, contacts

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## Subsurface Conditions

- Soils
  - sands, silts, clays
  - Gravels, cobbles, boulders
- Mixed Face Ground
  - Dissimilar rock strengths
  - Rocks and soils
  - Sands overlying clays
- Hydrology
  - Above the water table
  - Below the water table
  - Subaqueous

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# Tunneling Methods

| | Rock | Soft Ground |
|---|---|---|
| ➢ *Drill and blast tunneling* | √ | |
| ➢ *TBMs/Roadheaders* | √ | |
| ➢ *Sequential excavation* | √ | √ |
| ➢ *Shields/Pressurized face* | √ | √ |
| ➢ *Precast concrete linings* | √ | √ |
| ➢ *Jacked box tunnels* | | √ |

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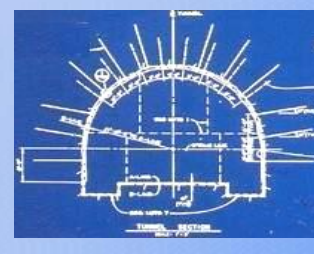
# Hard Rock – Drill and Blast

- Objective – remove the rock with minimum of blast damage
  - More holes, low charge weight / delay
  - Smooth wall blasting methods
- Excavation Sequencing
  - Small diameter – full face “rounds”
  - Larger diameter – sequential excavation



# Hard Rock - Drill and Blast

H-Series Atlas Copco Rocket Boomer

Unigel Cartridges

Trim Tex air-cushioned cartridges


Nonel Primadet blasting caps

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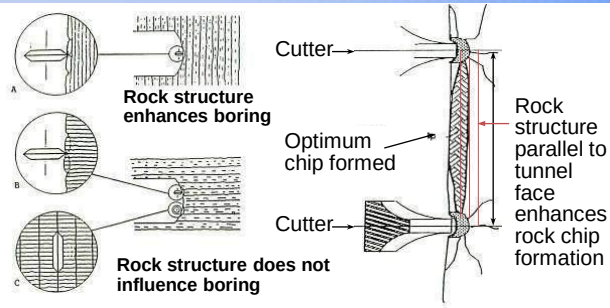
# Hard Rock - TBMs

- Rotating cutter head
- Discs mounted on cutter head
- Forward propulsion system
- Mechanical muck removal
- Forward propulsion system
- Ground support equipment

TBM disc cutters




Drive direction

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## Roadheaders

- Rotating cutter head(s)
- Articulating boom
- Mechanical mucking
- Variable shape openings

## Sequential Excavation Method

- Sequential Excavation Method
- aka New Austrian Tunneling Method (NATM)
- (engineered by a New Austrian…)
- aka North American Tunneling Method
- aka Not Anyone's Tunneling Method

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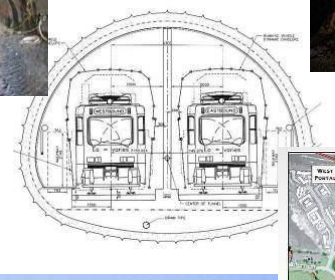
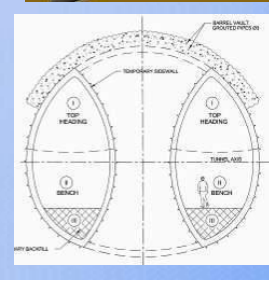
# SEM Examples

Mission Valley East LRT
San Diego State University




# SEM Examples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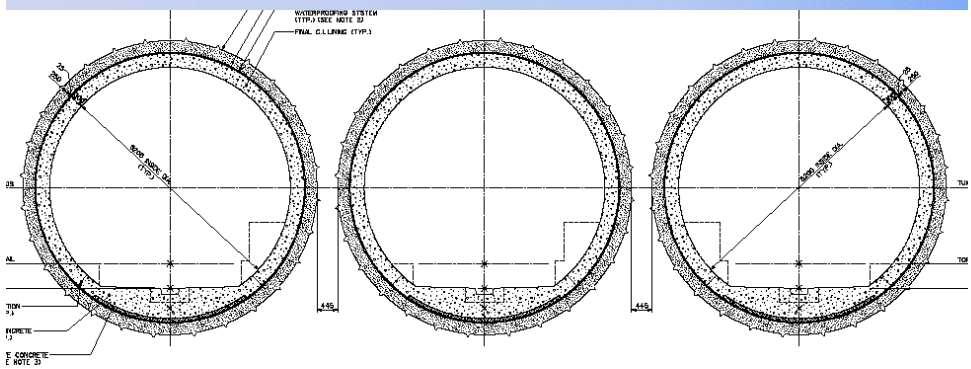
# SEM Example: Toronto's Spadina Subway Extension

## Triple Tunnels with Narrow Pillar



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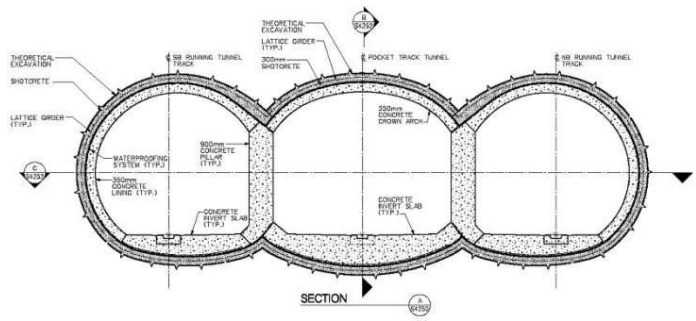
# Completed Structure

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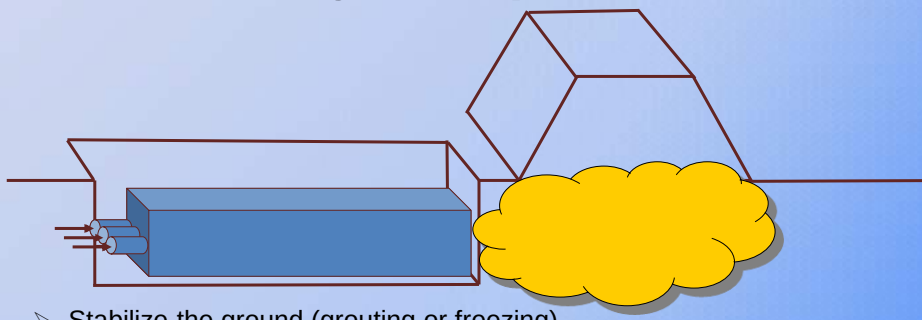
# Box Jacking Principles



- Stabilize the ground (grouting or freezing)
- Excavate jacking pit on one side of crossing
- Cast structure within jacking pit
- Position Jacking Rams
- Apply jacking force
- Excavate ground, extend rams, and jack box forward

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# Box Jacking – Central Artery

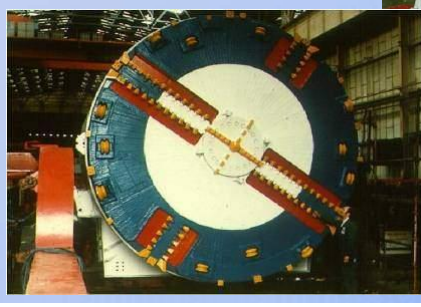
Table 1. Key Tunnel Dimensions

| Tunnel | Width (ft) | Height (ft) | Length (ft) | Weight (tons) | Max. Design Jacking Loads At RJS (tons) | Max. Design Jacking Loads At IJS (tons) |
|---|---|---|---|---|---|---|
| Ramp D | 78 | 38 | 167 | 17,000 | 12,600 | 14,000 |
| I-90 WB | 78 | 38 | 258 | 27,000 | 12,000 | 16,500 |
| I-90 EB | 79 | 35.5 | 359 | 31,000 | 12,800 | 18,000 |

RJS = rear jacking station; IJS = intermediate jacking station.

## Soft Ground Tunneling

- Open face shields
- Closed face machines
- Pressurized face machines



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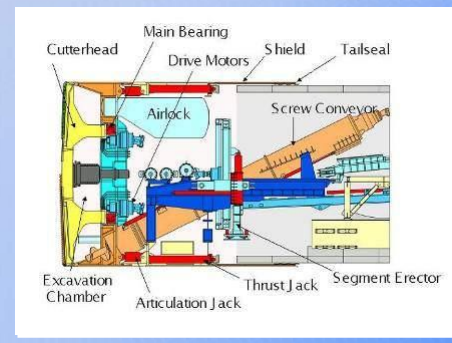
## Open Face / Closed Face

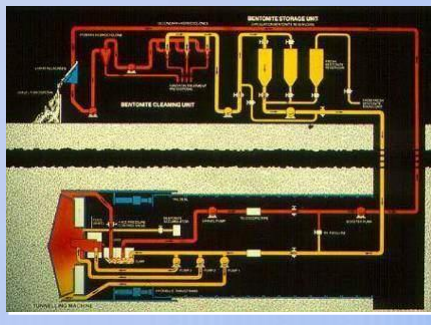
- Open face
  - Shields
  - machines

- Closed face (cutter wheels)

# Pressurized Face: EPB vs Slurry

- Earth pressure balance machine (EPBM)



- Slurry pressure machine

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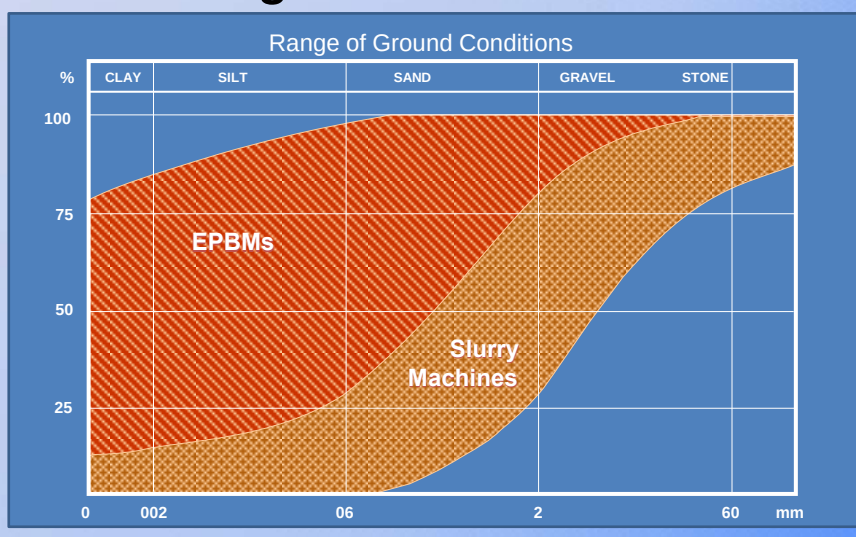
# Soil Grading Curves

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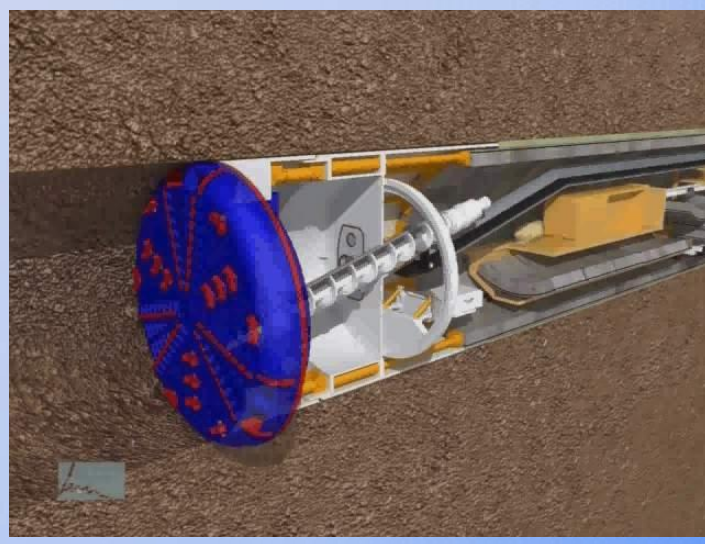
# EPB Fundamentals



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# EPBM - Additives

- Objective
  - Thicken sands
  - Reduce friction and abrasion
  - Increase homogeneity
  - Reduce stickiness
  - Reduce power demand
- Materials
  - Bentonite. 3% - 5% mix
  - Long Chain Polymers. 0.1% - 0.5% mix
  - Foam. 3% - 10% mix

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## Conditioned Soil

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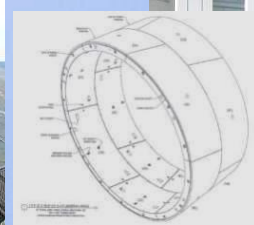
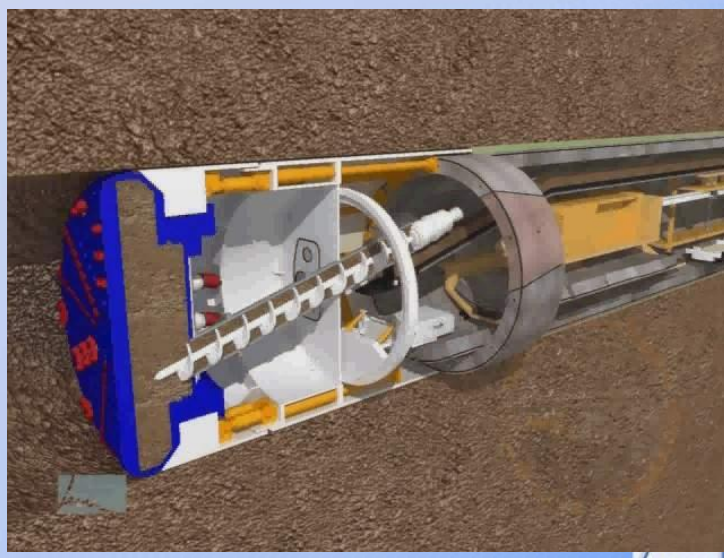
## Precast Concrete Lining

- Precast concrete segments
  - gasketed
  - Bolted
- Segment erector



# Assembly of Precast Concrete Ring



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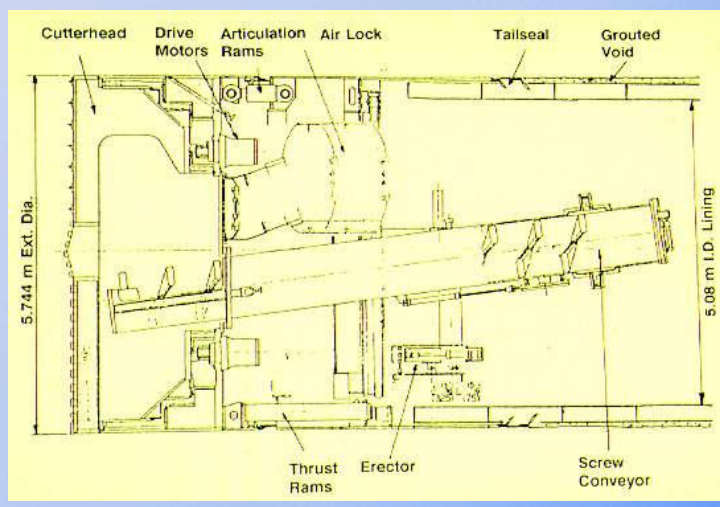
# Anacostia, Washington, DC EPBM

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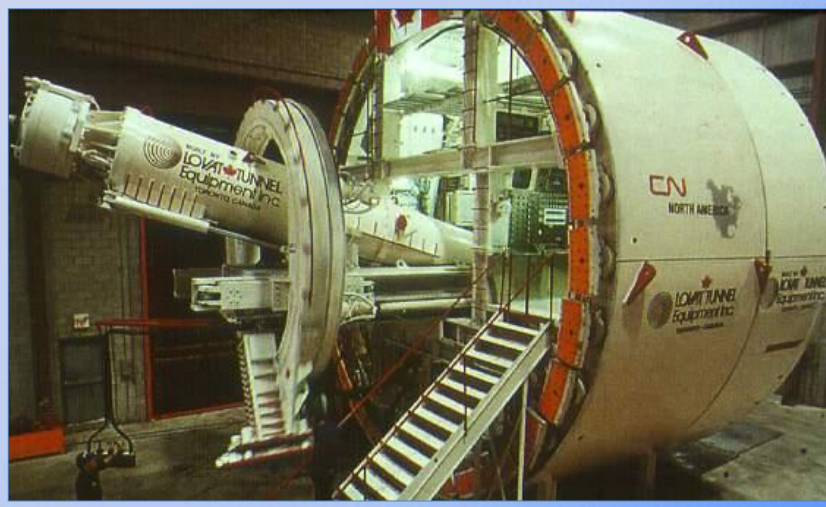
## St. Clair River Tunnel EPBM

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## Toronto Sheppard Subway EPBMs


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# Hydroshield or Mixshield

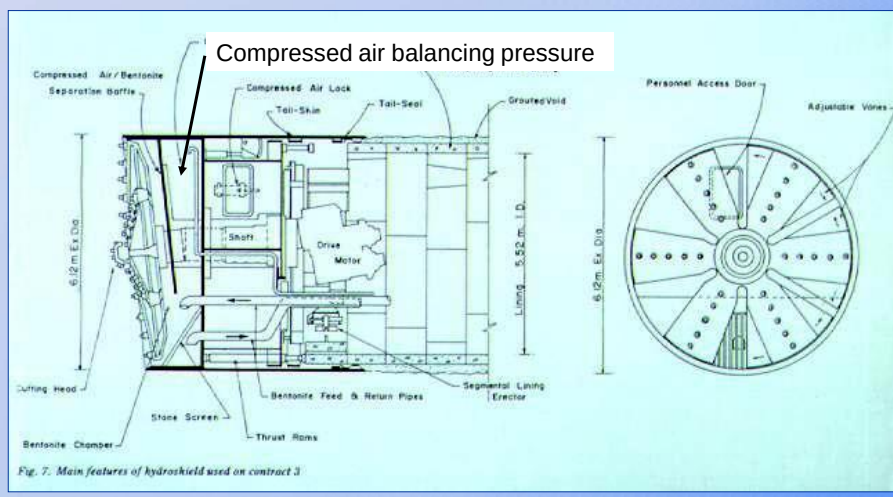

Fig. 7. Main features of hydroshield used on contract 3

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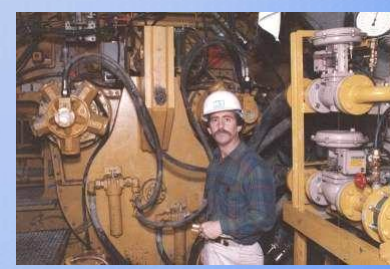
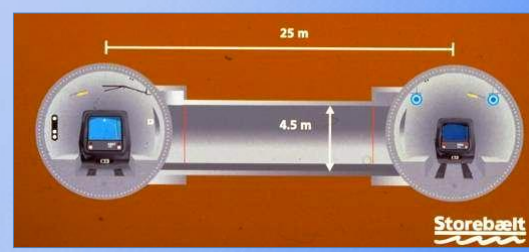
# Hochtief Hydroshield



# SMART Tunnel - Kuala Lumpur


# Cross Passages

- Criteria / Requirements
  - Spacings
    - Typically 700 to 1,000 feet
    - Emergency egress during fire events
    - Adjust locations to suit ground conditions
  - Construction
    - Facilitate break-out from mined tunnels
    - Prevent ground loss and settlement

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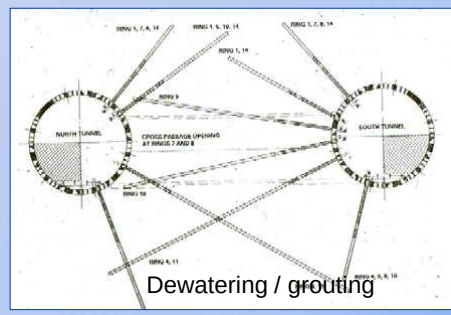
# Cross Passages

- Ground Modification
  - Use methods such as grouting, dewatering, and freezing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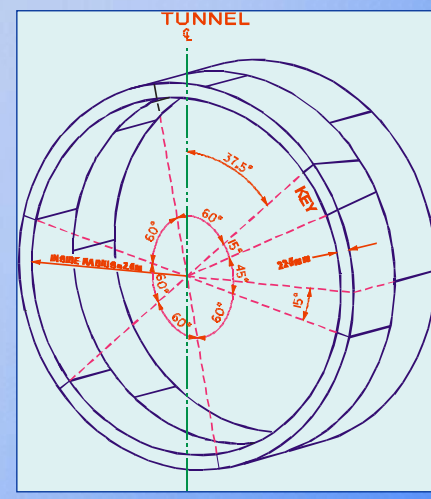
# Cross Passages

- Construction Methods
  - Install “Specials”
  - Removable bolted segments
  - Hybrid concrete/ cast iron

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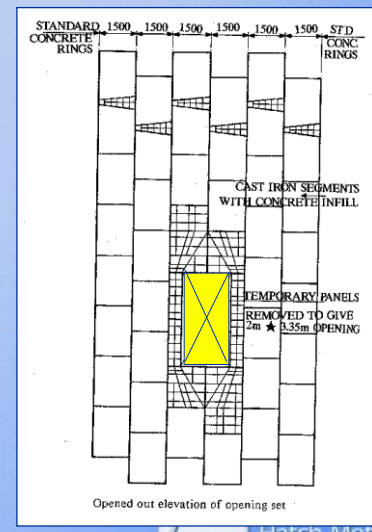
# Cross Passages

- Construction Methods
  - Special Composite Segments
    - Cast iron with concrete infill
    - No taper
    - 9 in thick
    - Standard 4.5 to 5 ft wide segments
    - Remove temporary panels to provide 6.5 x 11 ft opening

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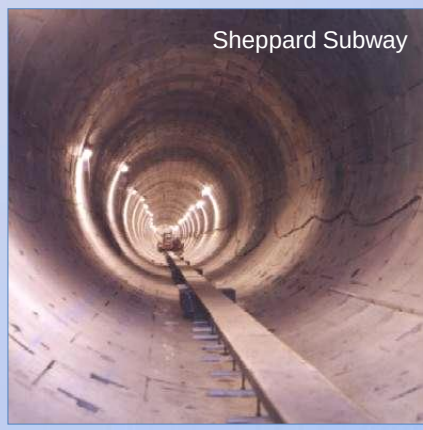
# Cross Passages, Sheppard Subway




Construction Methods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# Cross Passages, Sheppard Subway



Construction Methods

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# Cross Passages, Sheppard Subway

Completed cross-passage construction

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## Risk Management

- Geologic Uncertainty
- Risk Registers

## 8 Tunneling "Facts of Life"

| | | |
|---|---|---|
| Tunnel projects are linear and can extend for miles | Subsurface conditions can vary significantly along the alignment | Subsurface conditions influence means, methods, and construction cost |
| Underground "surprises" = commercial risk | Contractors do not *accept* risk, they *price* risk | It's better to anticipate a risk event than be surprised |
| Owners want the lowest cost of construction for their projects | Contracts that anticipate risks will result in lower cost and fewer claims | |

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## Prepare a Geotechnical Baseline Report to

- Describe anticipated subsurface conditions
- Describe how those conditions will influence construction
- Describe how those conditions have influenced the design
- Identify key risks on the project
- Describe who carries the risks for conditions inside and beyond the "baselines"
- Avoid protracted legal battles

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## What is a Geotechnical Baseline Report

- A Contract Document
- A set of contractual assumptions – not necessarily geotechnical "fact"
- A guidance document for bidding the project
- A tool to help manage risks during construction
- A means for administering the Differing Site Conditions clause under the Contract

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## How a GBR Works to Reduce Claims

- Baselines identify and allocate risk
- Baselines should be a reasonable extension of the available information
- Assume the baseline is a “line in the sand”


- Can set provisional sums for potential conditions outside the baselines
- Owner pays the provisional sums ONLY IF adverse conditions are encountered

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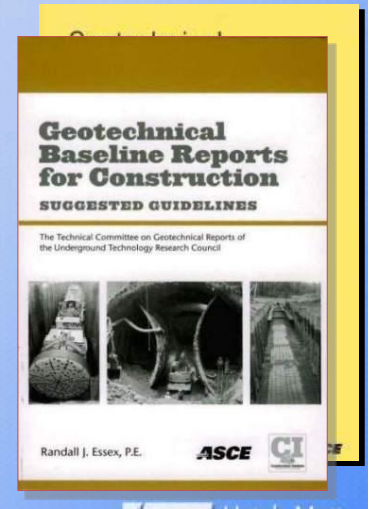
## ASCE Guidelines Publications

- First Published in 1997
- Updated Edition in 2007
- Reflects
  - 30 years of practice
  - Several industry feedback forums
  - The industry’s views on GBR preparation and use

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## What We Mean by Risk

*. . . the combination of the probability and impact of an occurrence or circumstance that may adversely affect the successful completion of your project. . .*

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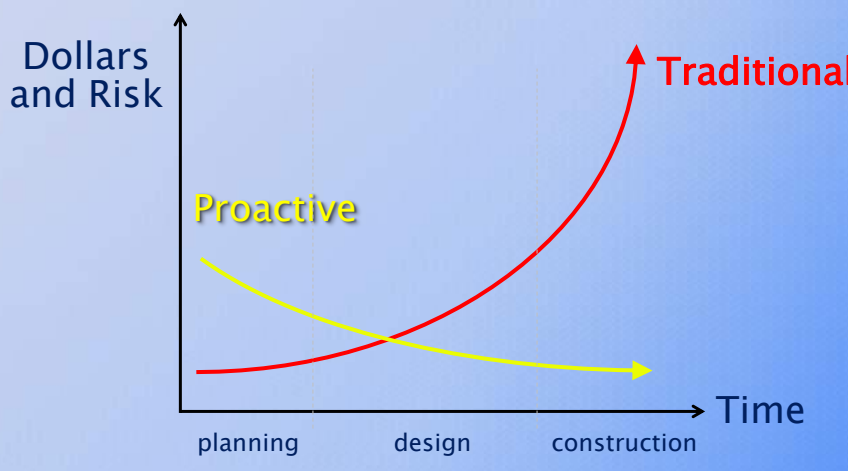
## It Pays to be Proactive…

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## Types of Risks

- Regulatory/Permitting
- Design/Operational
- Financial/Commercial/Contractual
- Site Access/Logistics
- Construction
- Environmental
- Health/Safety/Security

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## We Recommend a Collaborative Approach to Managing Risk


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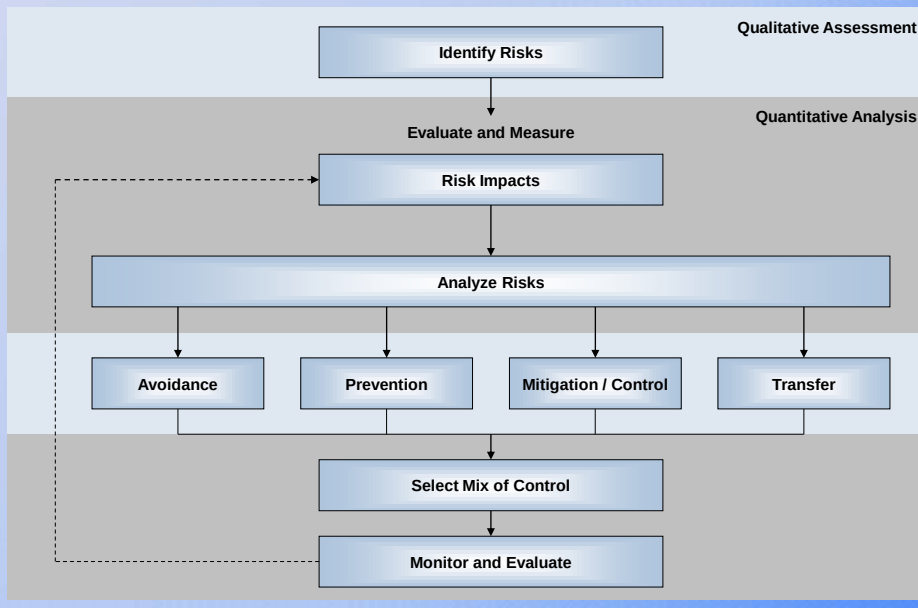
# Qualitative and Quantitative Assessments

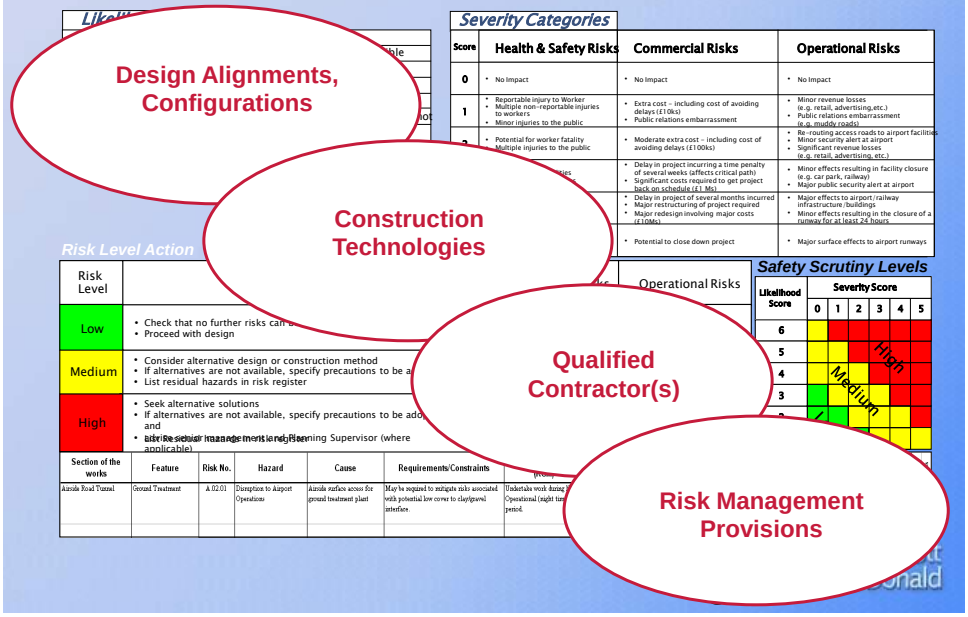



# Identify, Evaluate, and Quantify

| Probability | Consequence | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| 6 | | | | | | |
| 5 | | | | | | |
| 4 | | | | | | |
| 3 | | | | | | |
| 2 | | | | | | |
| 1 | | | | | | |

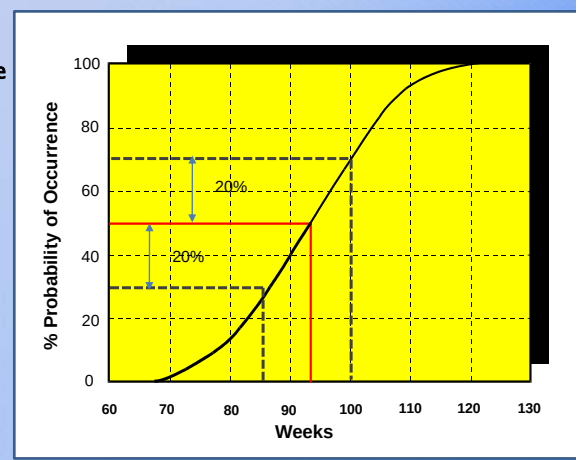
High
Medium
Low

# Results Summarized in a Risk Register




# Monte Carlo @Risk Analysis

- Project Schedule Example
  - 93 weeks – most likely
  - 87 weeks – shortest credible
  - 100 weeks – longest credible
  - 90% envelope: 108 weeks

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# Contract Delivery Methods


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# Contract Delivery Methods

**Contractor Compensation**
- Fixed Price - Lump sum with schedule of values
- Fixed Price – Unit Prices with upset limit
- Cost Reimbursable / fixed fee
- Target Cost / incentive fee

**Contract Form**
- Design-Bid-Build
- Design-Build
- Early Contractor Involvement
- CM At Risk

**Financing**
- Public Funds
- Public/Private Combinations
- Fully Private Funds

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## Summary

- Tunnels are different
- Respect function and shape
- Use the right technologies
- The earlier the contractor's involvement, the better
- Pay the contractor fairly for the work performed
- Keep the lawyers out of our business

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## Federal Transit Administration
## 27th Annual Engineer's Week

# Questions

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